

VIPR Gas Path Diagnostic Results



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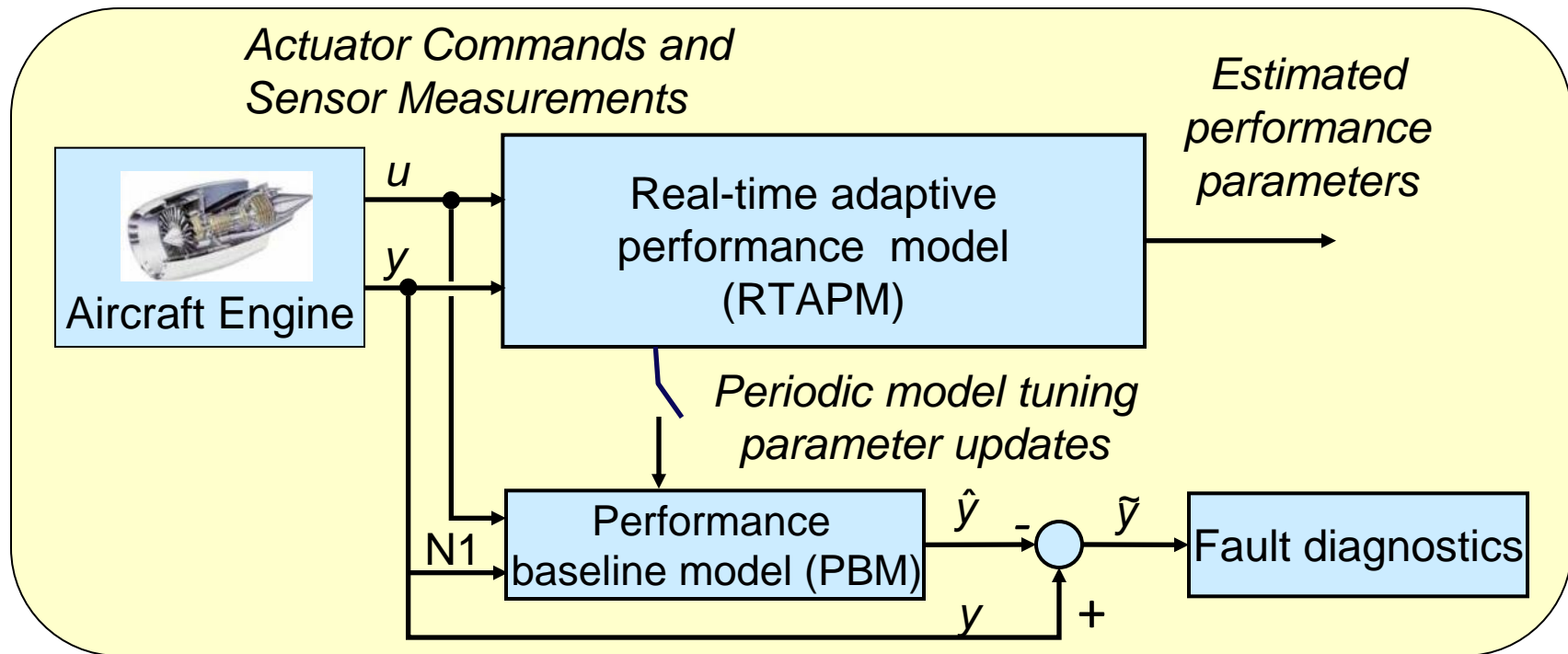
Cleveland, OH



Outline

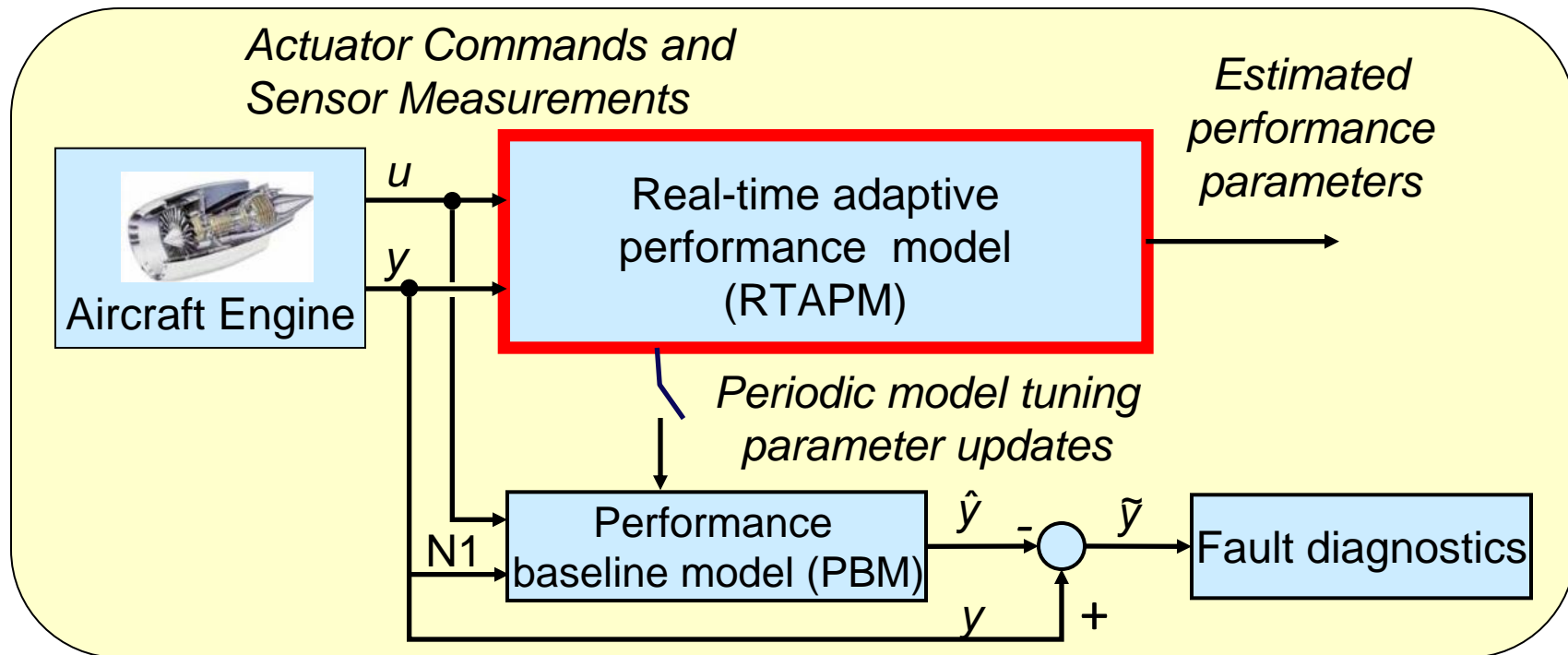
- Model-Based Gas Path Diagnostic Architecture Overview
- Application Example: VIPR Engine Test Data
 - VIPR Engine Health Management (EHM) Test Architecture
 - Model Enhancements
 - Diagnostic results
- Summary

Model-Based Gas Path Diagnostic Architecture



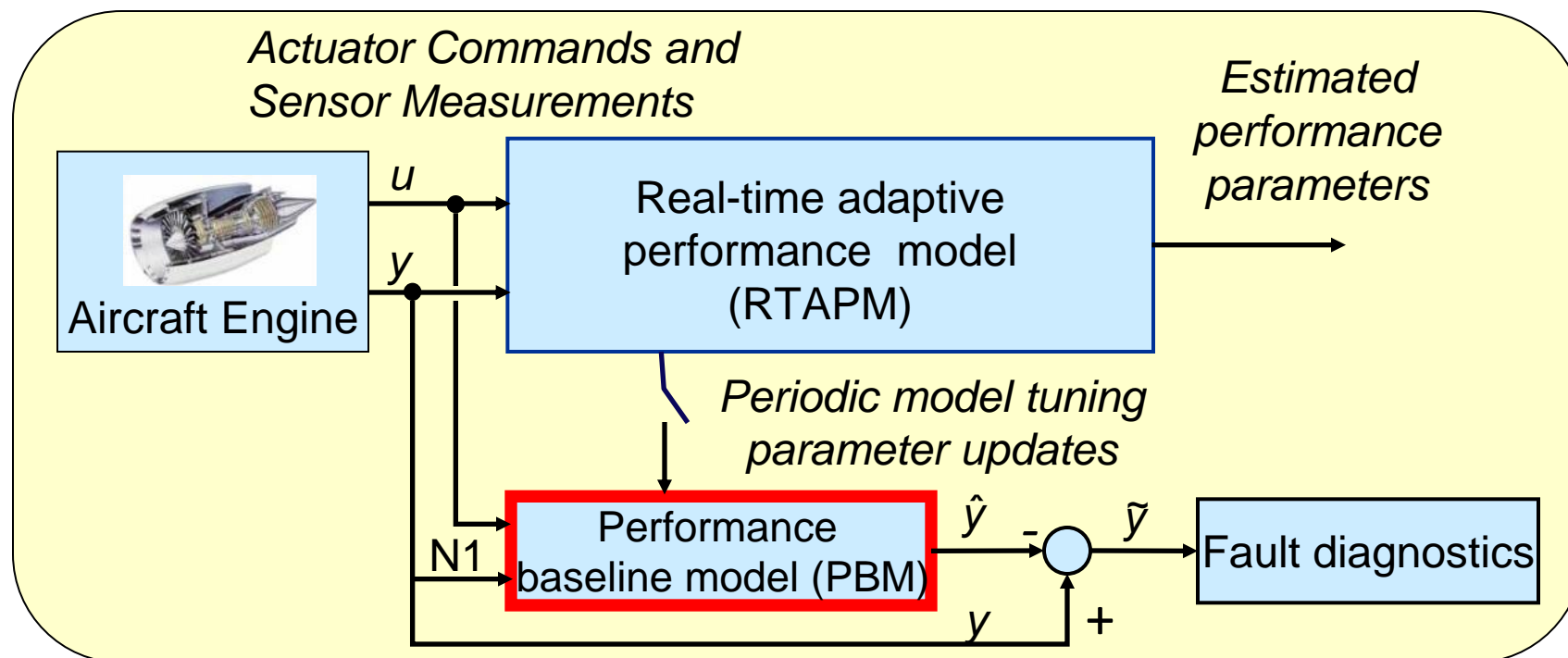
- Designed for processing real-time continuous (streaming) engine measurement data to provide:
 - Estimation and trending of deterioration-induced engine performance changes
 - Detection and isolation of gas path system faults

Real-Time Adaptive Performance Model (RTAPM)



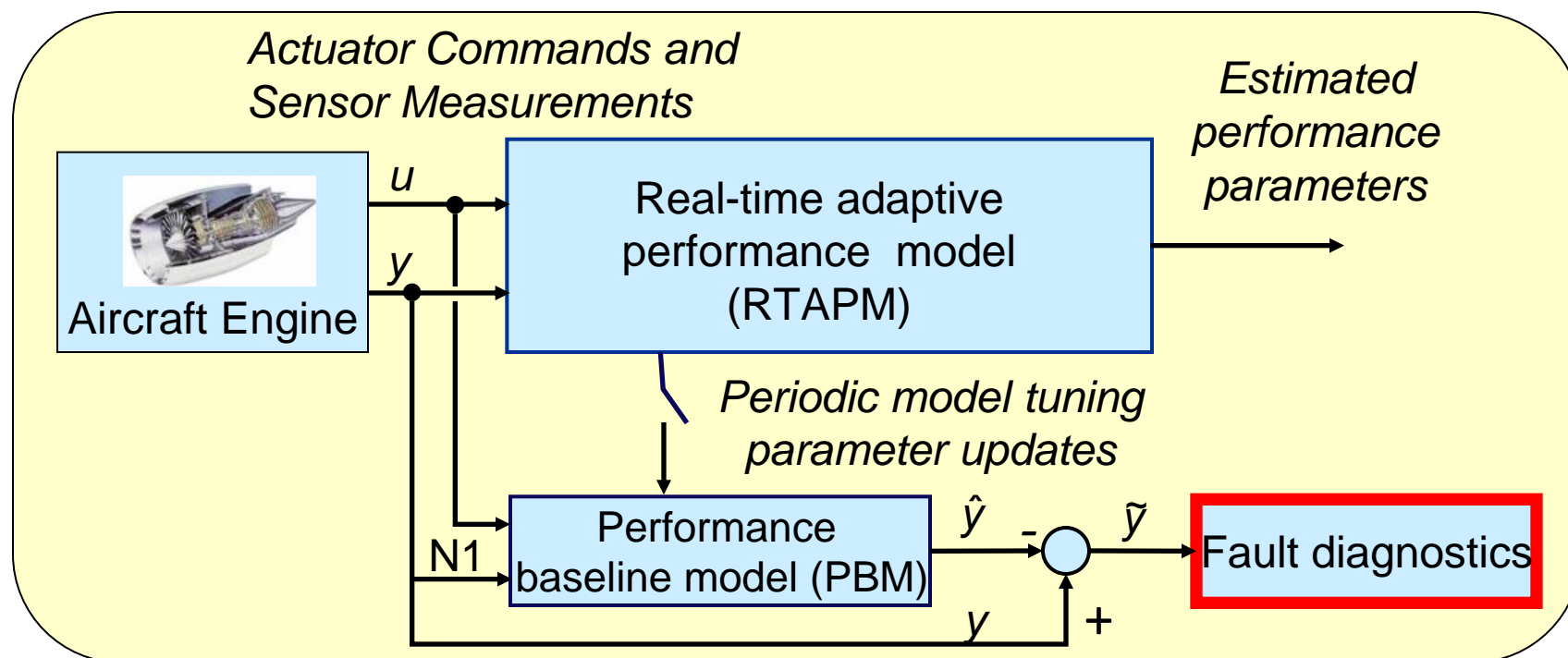
- Self-tuning piecewise linear Kalman filter design
- Applies NASA-developed optimal tuner selection methodology
 - Applicable for underdetermined estimation problems
 - Minimizes mean squared estimation error in parameters of interest
- Provides real-time estimates of unmeasured engine performance parameters
 - Applicable for performance trend monitoring and model-based control applications

Performance Baseline Model (PBM)



- Piecewise linear state space model design, run “pseudo open-loop” with inputs of:
 - Actuator commands, u .
 - Sensed fan speed, $N1$, which is used for setting model fan speed state variable to improve model-to-engine tracking capability.
 - Periodic model tuning parameter updates from RTAPM to account for gradual performance degradation effects.
- Provides a baseline of recent past engine performance

Fault Diagnostics



- Monitors residuals between sensed engine outputs and PBM estimated outputs.
- Fault detection is performed by calculating and monitoring a weighted sum of squared residuals (WSSR) signal.
- Upon fault detection, fault classification is performed by identifying the candidate fault signature that most closely matches the observed residuals in a weighted least squares sense.

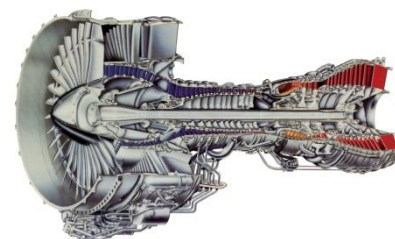


VIPR Engine Test

- VIPR is a series of engine tests ongoing at NASA Dryden / Edwards Air Force Base
- Test vehicle:
 - Boeing C-17 Globemaster III
 - Equipped with Pratt & Whitney F117 high-bypass turbofan engines
- VIPR 1 EHM ground tests include:
 - A series of nominal and faulted engine test cases
 - Data collected over a range of engine power settings including quasi-steady-state and transient operating conditions



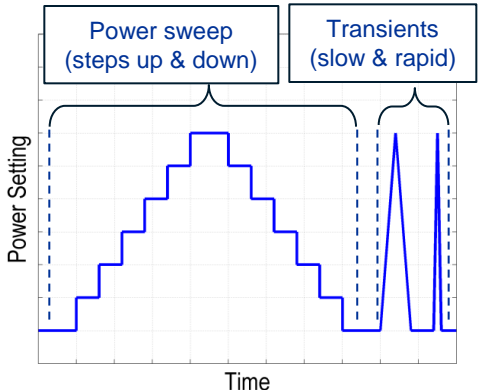
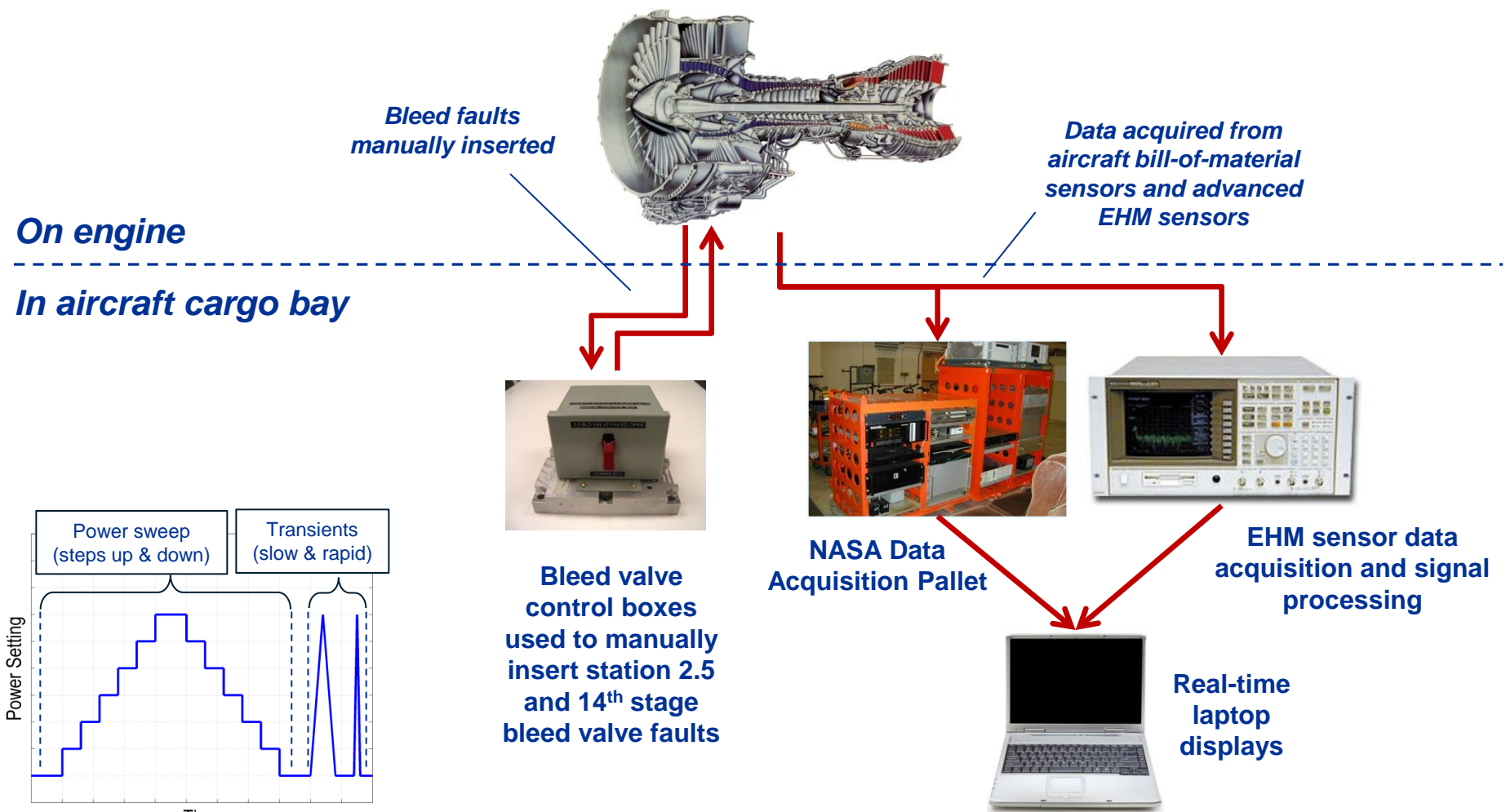
Boeing C-17 Globemaster III



Pratt & Whitney F117 Turbofan Engine



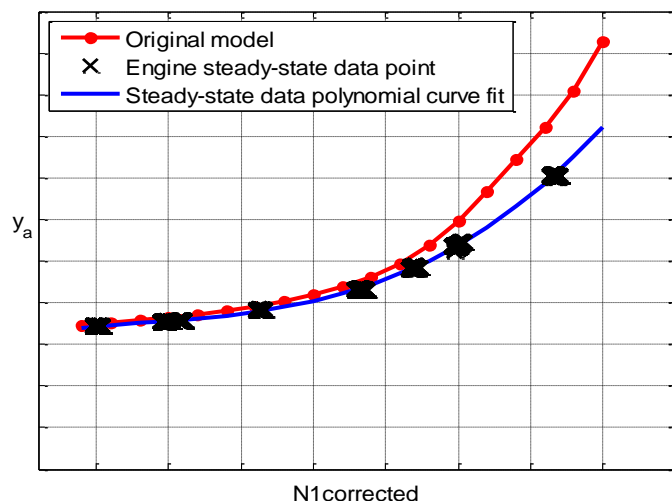
VIPR Architecture for EHM Testing



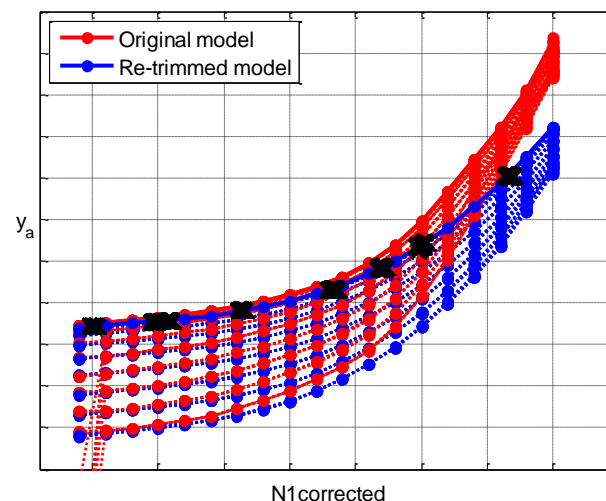
VIPR Event Test Sequence (notional)

Model-Based Gas Path Diagnostic Architecture Enhancements

- Model-based gas path diagnostic architecture designed based on NASA C-MAPSS40k model.
- Model updates were necessary due to notable mismatch between F117 engine and C-MAPSS40k model:
 - Re-trimmed piecewise linear model to match F117 engine performance
 - Updated model thermocouple dynamics



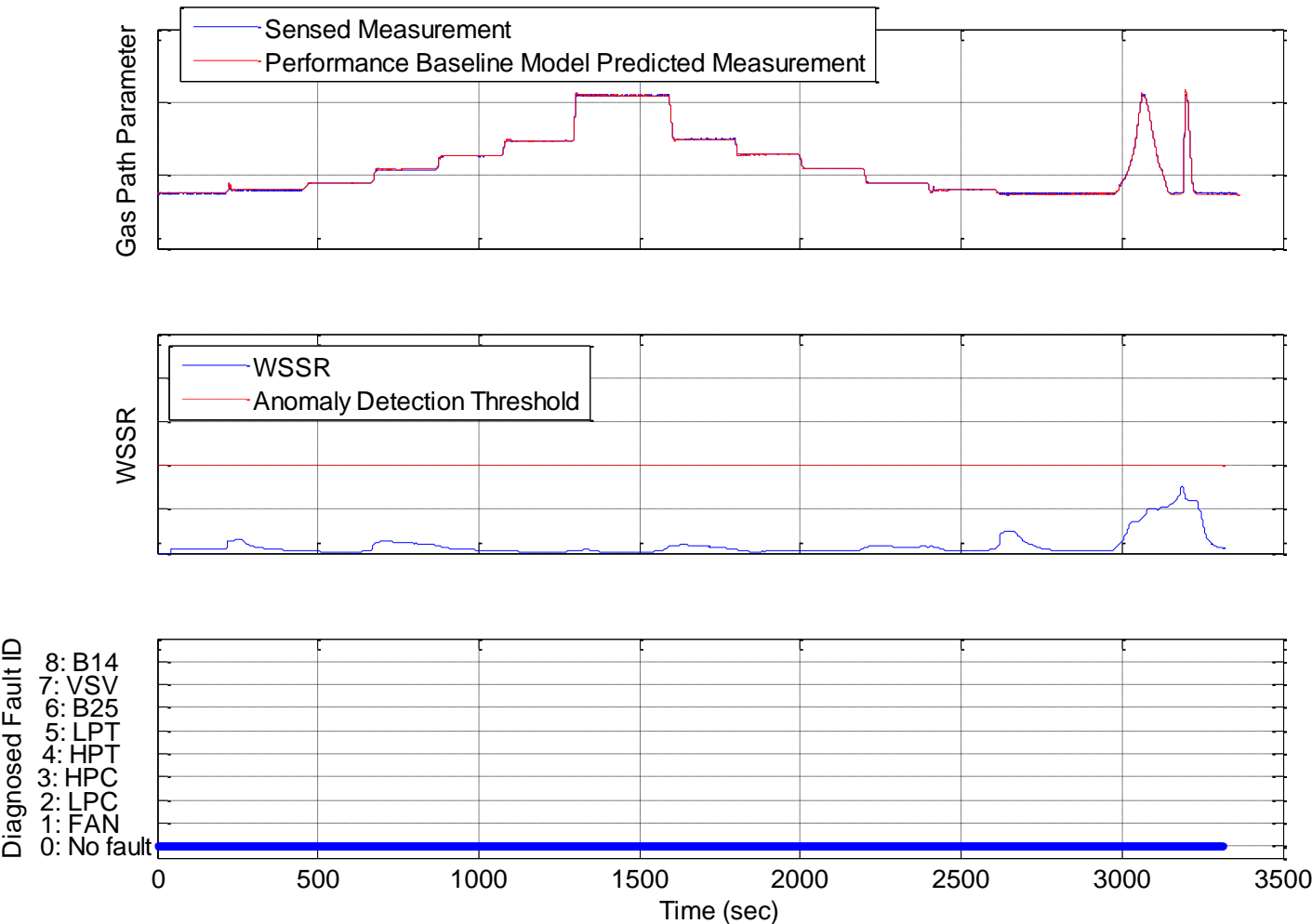
Original model and polynomial curve fit through acquired steady-state data (parameter y_a)



Original and re-trimmed PWLM (parameter y_a)

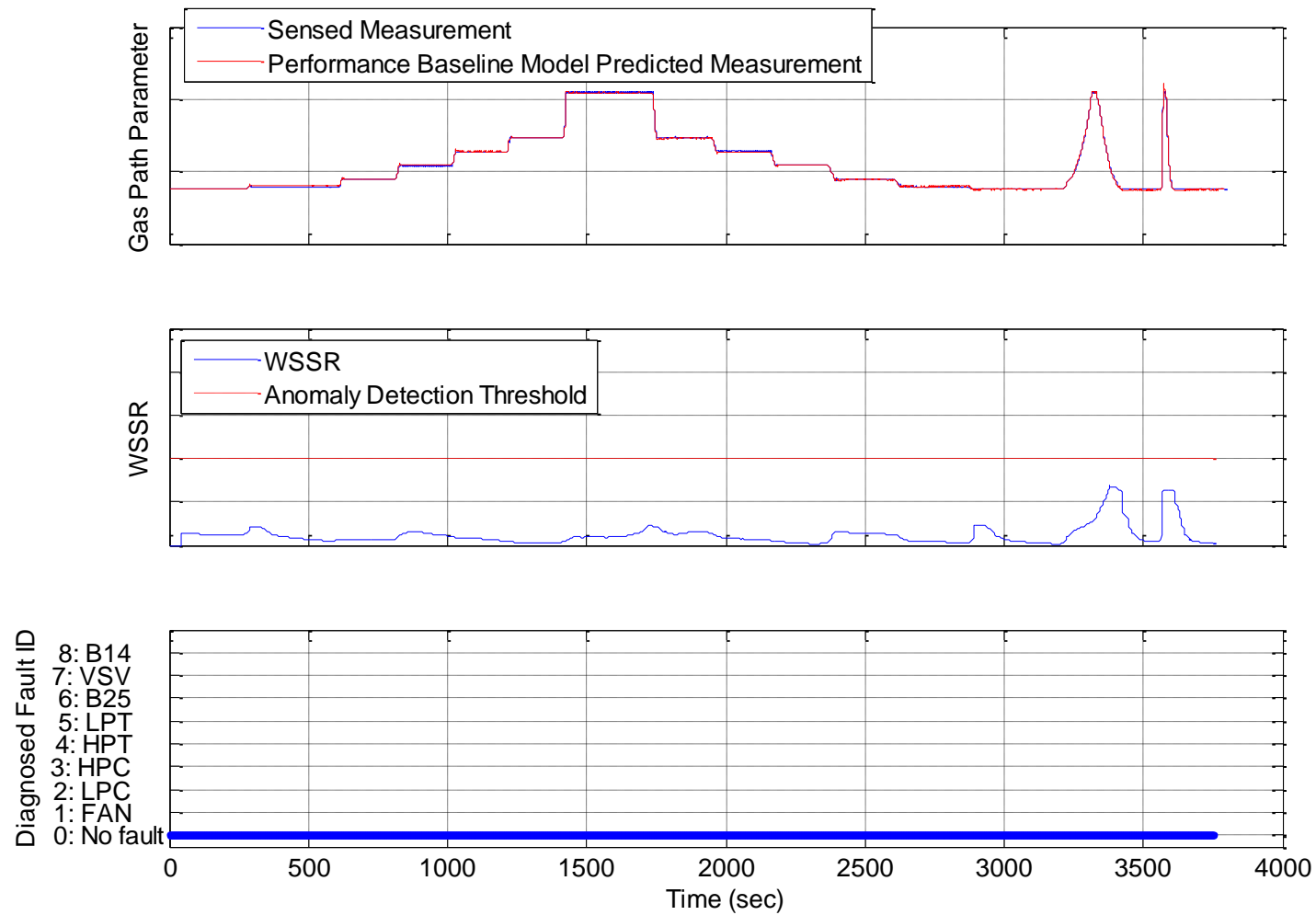


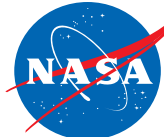
Diagnostic Results (Baseline Run #1)



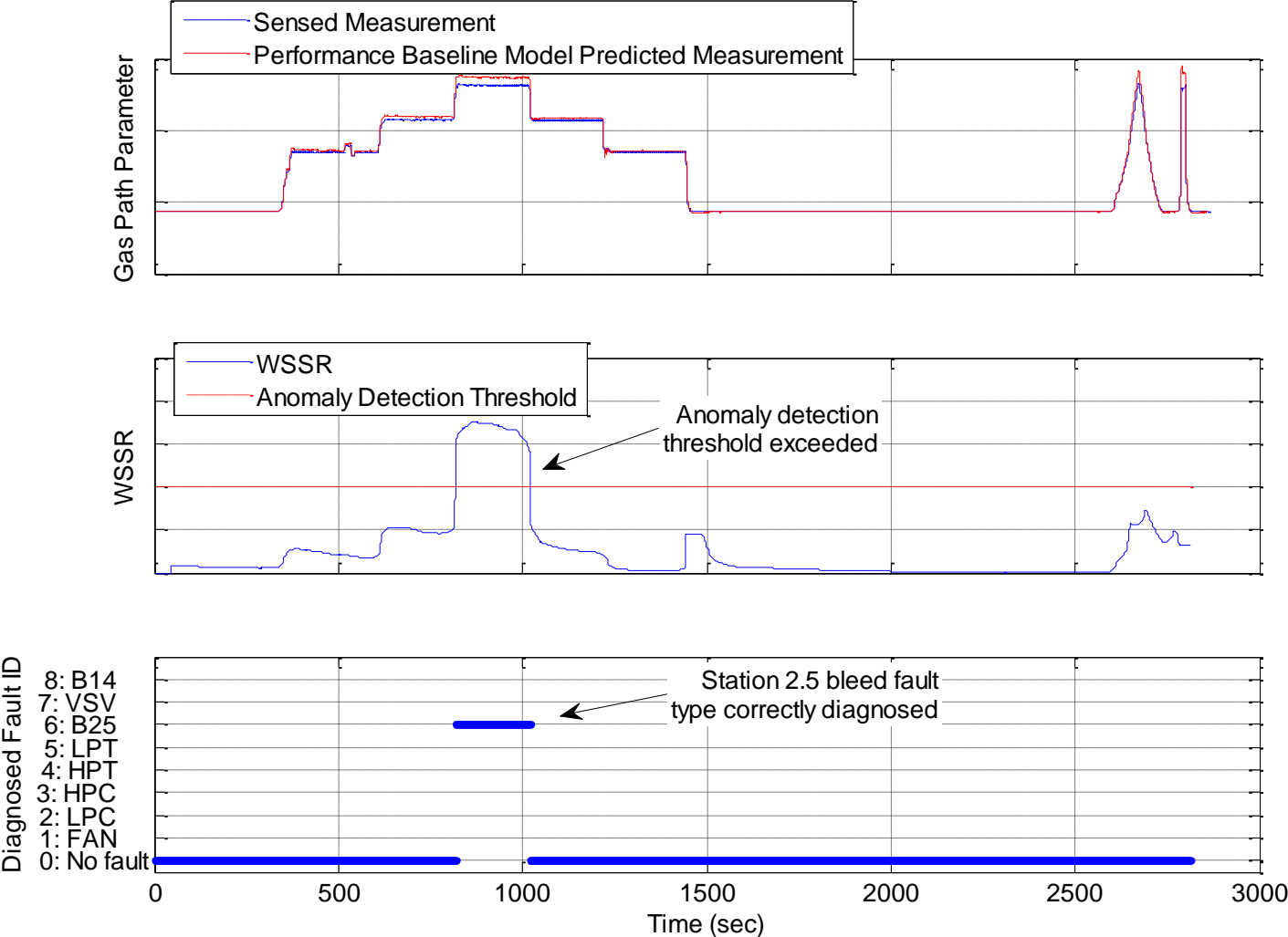


Diagnostic Results (Baseline Run #2)



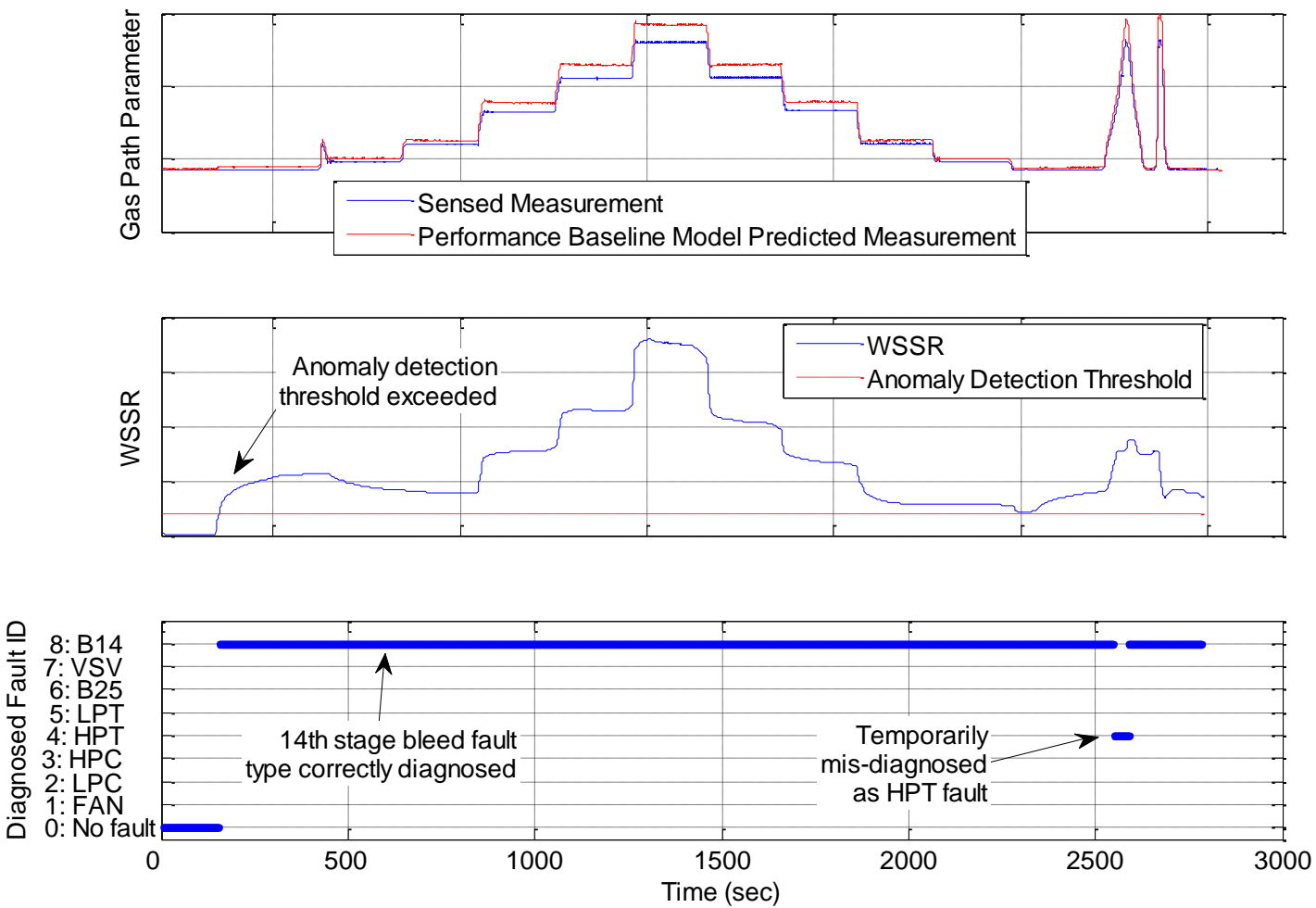


Station 2.5 Bleed Valve Fault Case





14th Stage Bleed Valve Fault Case





Summary

- Model-Based Gas Path Diagnostic Architecture successfully applied for processing streaming (continuous) aircraft engine measurement data
- Model enhancements to address engine-model mismatch were necessary
 - Re-trimming of steady-state trim points
 - Updating thermocouple dynamics
- Future work to focus on
 - Improving model-to-engine matching during transients
 - Evaluating architecture's ability to estimate and trend engine performance deterioration



References

- Optimal Tuner Selection

- Simon, D.L., Garg, S., (2010), "Optimal Tuner Selection for Kalman Filter-Based Aircraft Engine Performance Estimation," *Journal of Engineering for Gas Turbines and Power*, Vol. 132 / 0231601-1.
- Simon, D. L., Armstrong, J. B., Garg, S., (2011), "Application of an Optimal Tuner Selection Approach for On-Board Self-Tuning Engine Models," ASME-GT2011-46408, 2011 ASME Turbo Expo, Vancouver, BC, Canada, June 6-10.

- Piecewise Linear Model Implementation

- Armstrong, J.B., Simon, D.L., (2012), "Constructing an Efficient Self-Tuning Aircraft Engine Model for Control and Health Management Applications," Annual Conference of the Prognostics and Health Management Society, Minneapolis, MN, Sep. 23-27.

- Model-Based Diagnostic Architecture

- Simon, D. L., (2010), "An Integrated Architecture for Onboard Aircraft Engine Performance Trend Monitoring and Gas Path Fault Diagnostics," Proceedings of The 2010 JANNAF Joint Subcommittee Meeting, Colorado Springs, CO, May 3-7.
- Armstrong, J.B., Simon, D.L., (2011), "Implementation of an Integrated On-Board Aircraft Engine Diagnostic Architecture," AIAA-2011-5859, 47th AIAA Joint Propulsion Conference & Exhibit, San Diego, CA, July 31-August 3.
- Simon, D.L., (2012), "An Integrated Approach for Aircraft Engine Performance Estimation and Fault Diagnostics," ASME-GT2012-69905, 2012 ASME Turbo Expo, Copenhagen, Denmark, June 11-15.

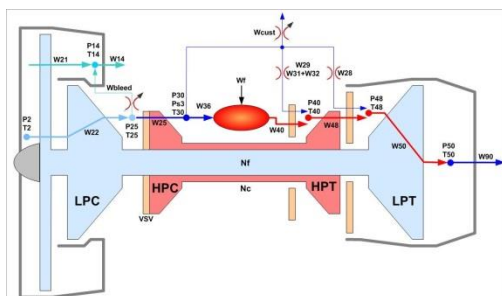


Backup Slides

Piecewise Linear Model (PWLM) Generation

1) Nonlinear Engine Model

- Physics-based aero-thermodynamic model
- Full-envelope transient simulation capabilities



Linearization

2) Linear Point Model Generation

- Linear state space model design
- Approximates nonlinear model dynamics near design point
- Generated at multiple design points spanning engine operating envelope

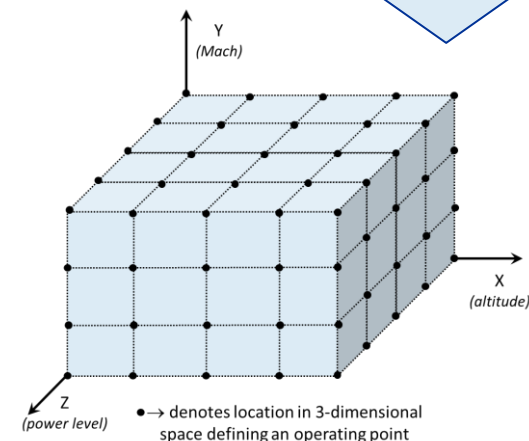
$$\dot{x} = A(x - x_{trim}) + B(u - u_{trim}) + L(h - h_{ref})$$

$$\dot{x} = A\Delta x + B\Delta u + L\Delta h$$

$$y - y_{trim} = C(x - x_{trim}) + D(u - u_{trim}) + M(h - h_{ref})$$

$$\Delta y = C\Delta x + D\Delta u + M\Delta h$$

Combined & scheduled for Interpolation



3) Piecewise Linear Model

- Comprising multiple linear point models
- Interpolation applied to enable transition between point models
- Approximates nonlinear model dynamics over entire operating envelope.